Formation and Feedback of Population III Stars

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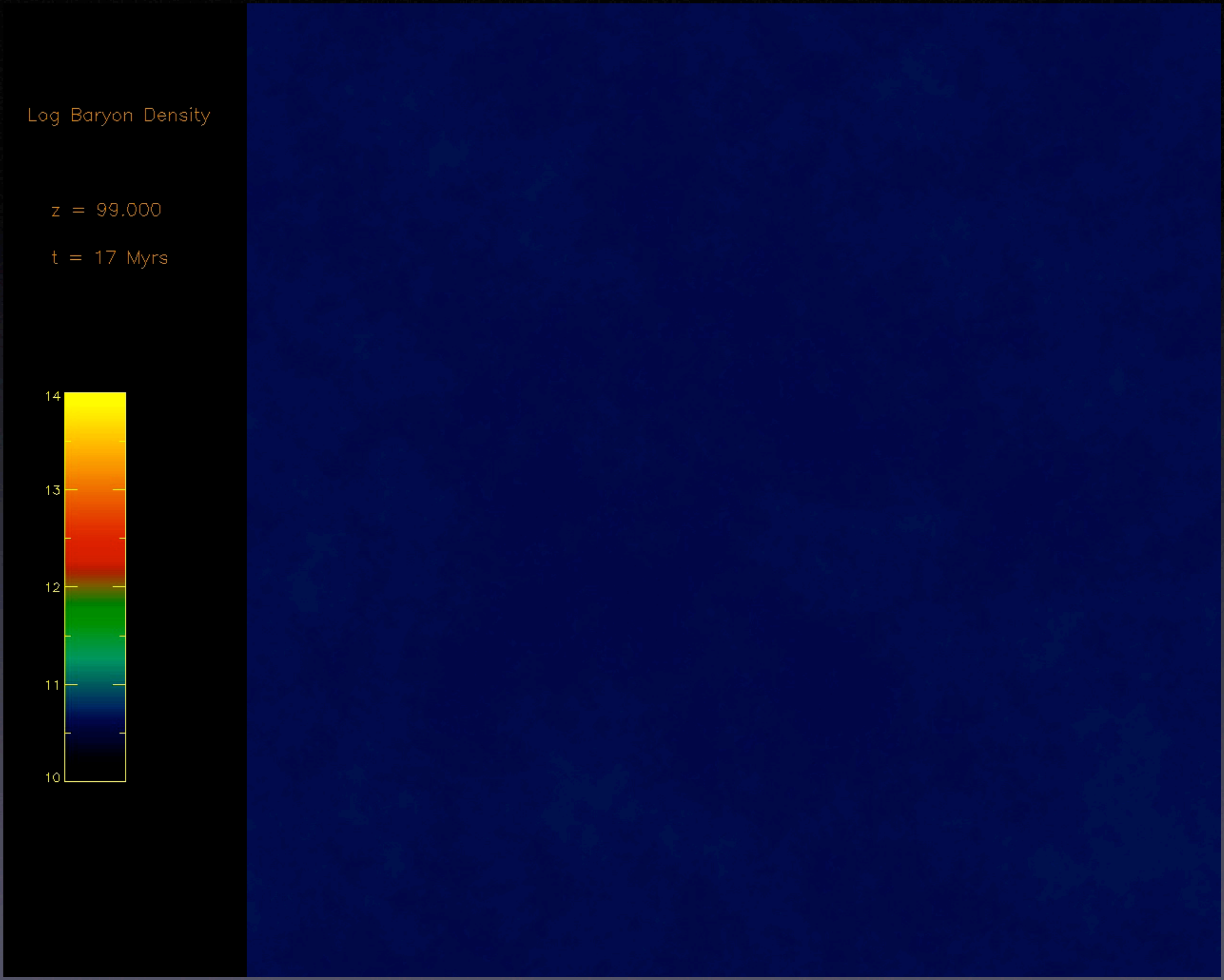
Guiding Questions in First Structure Formation

- What are the first structures of astrophysical interest?
- How do these objects form and evolve?
- What are their cosmological consequences?
- What are their observational signatures/remnants?
- What is the IMF of Population III stars?


Log Baryon Density
z = 99.000
t = 17 Myrs
14
13
12
11
10

Population III Star Formation

- A well-posed problem
  - Initial conditions can be taken from cosmology (CMB, LSS)
  - Simple but nonlinear physics - gravity, hydrodynamics
  - Simple non-equilibrium chemistry and optically thin radiative cooling - no dust or metals, just H, He (and H_2)
  - No dynamically important B-fields (we believe)
- Complexity due to large range of scales involved
  - $R_\odot/L_{LSS}$ $(z = 20) \sim 10^{-12}$
  - $P_\odot/t_{hubb}$ $(z = 20) \sim 10^{-12}$

H_2 chemistry and Pop III Stars

- H_2 is primary coolant - no metals!

- Pop III: T_{min} ~ 200 K, Galaxy: T_{min} ~ few K

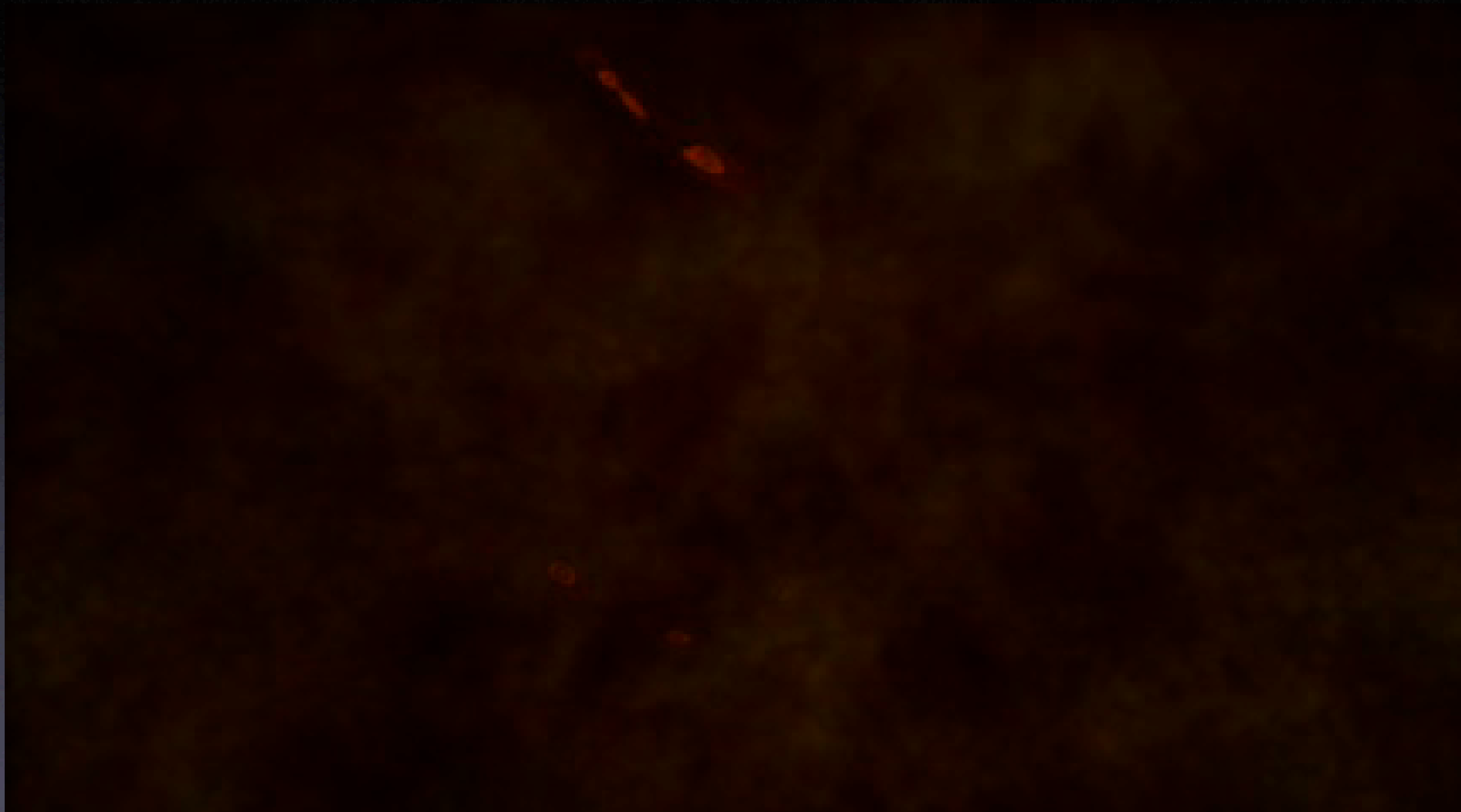
- Low density ($n \leq 10^8$ cm^{-3}) - residual electrons catalyze H_2 formation via H^- channel:

$$H + e^- \Rightarrow H^- + \gamma$$
$$H^- + H \Rightarrow H_2 + e^-$$

- High density ($n \geq 10^8$ cm^{-3}) - formation of H_2 via 3-body process:

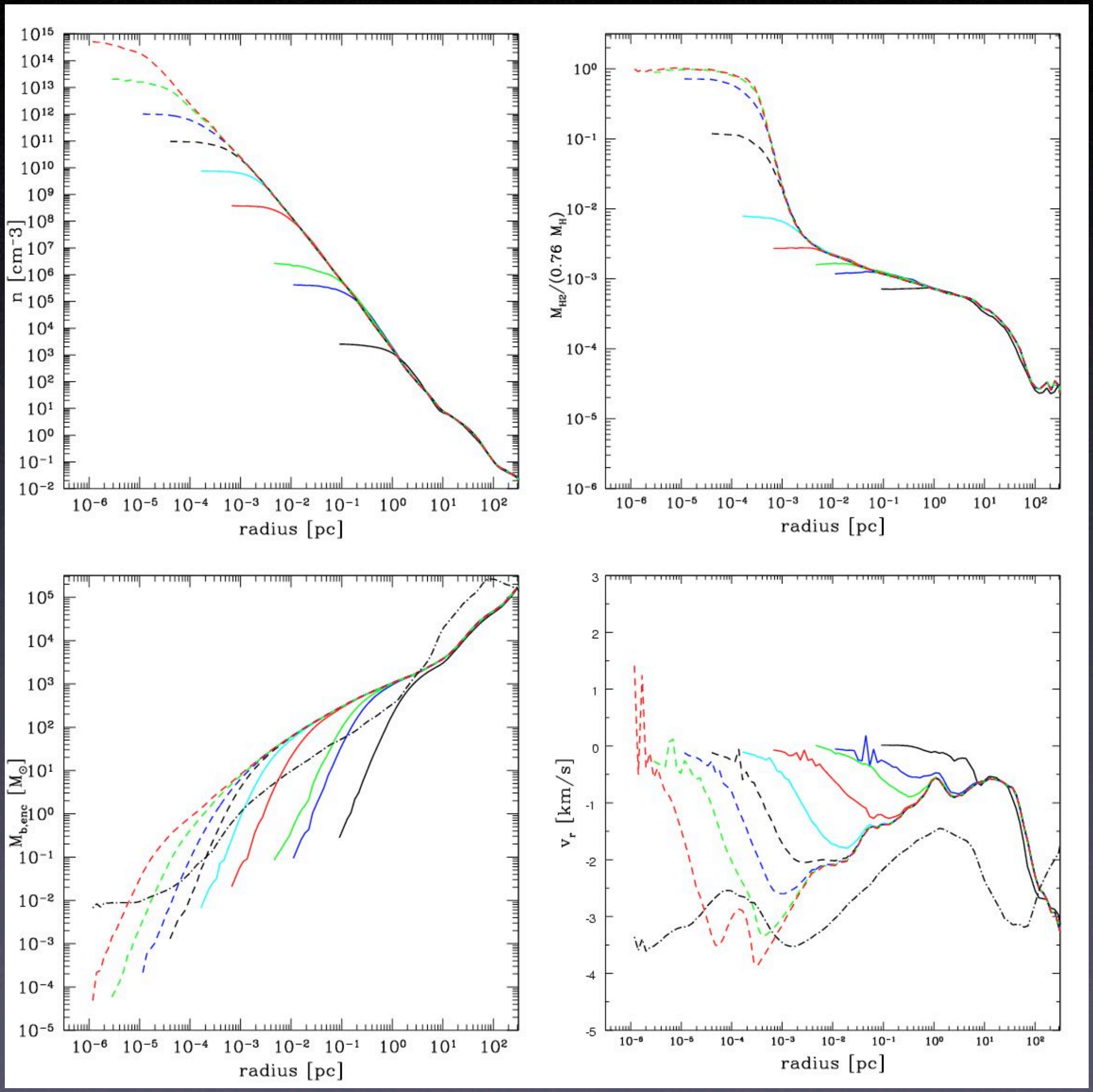
$$H+H+H \Rightarrow H_2 + H$$

Formation and death of a Pop III star



Movie courtesy T. Abel

Evolution of a single primordial protostellar core



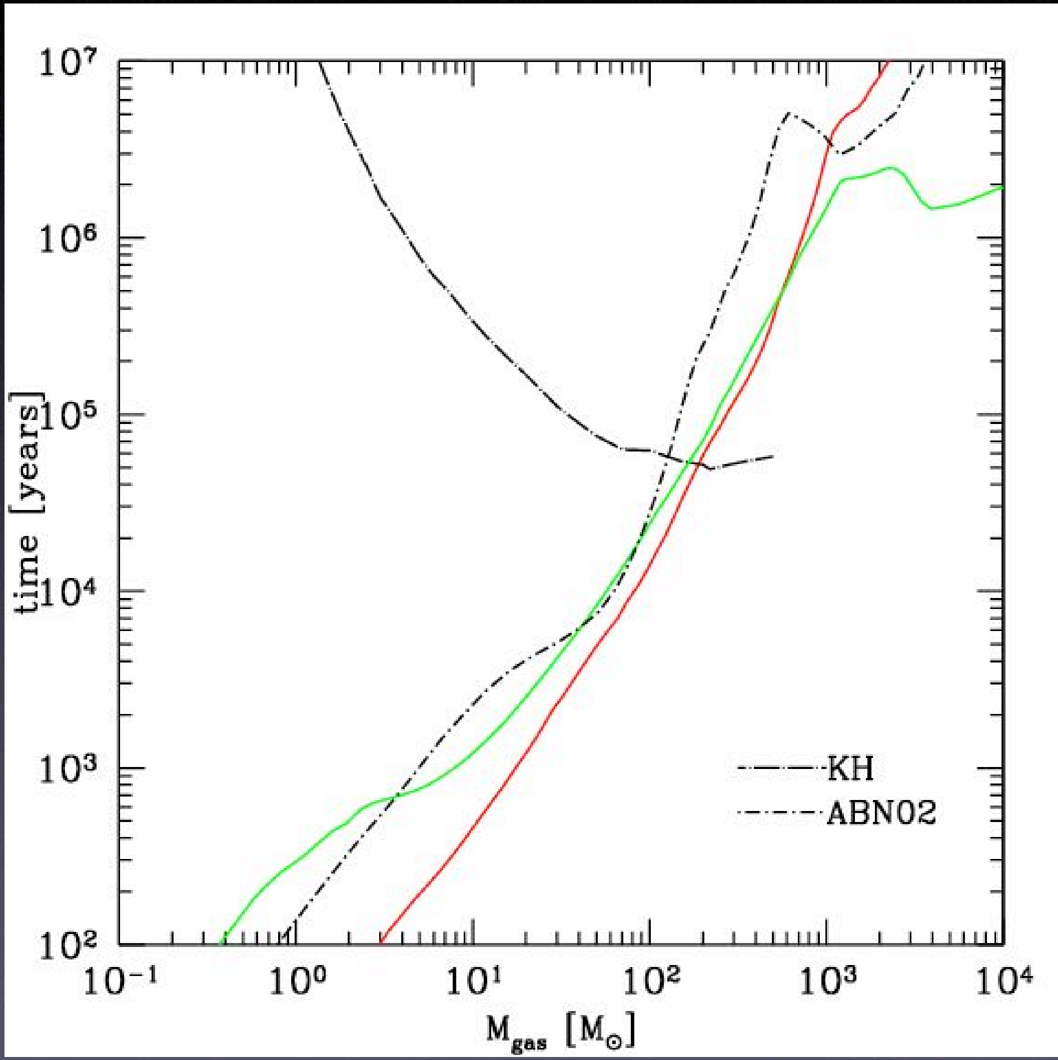
black sol. line: t = t_0, z=17.6
blue solid: t_0 + 8.75e5 yrs
green solid: +5e6 yrs
red solid: +3e5 yrs
cyan solid: +17,000 yrs
black dashed: +2300
blue dashed: +310 yrs
green dashed: +91 yrs
red dashed: +31 yrs

$M_{vir} = 4.67 \times 10^5\ M_\odot$

Evolution qualitatively similar to Abel et al. 2002

Important questions:
What is the final stellar mass?
Is this result robust?

Estimate Pop III stellar mass using accretion rates



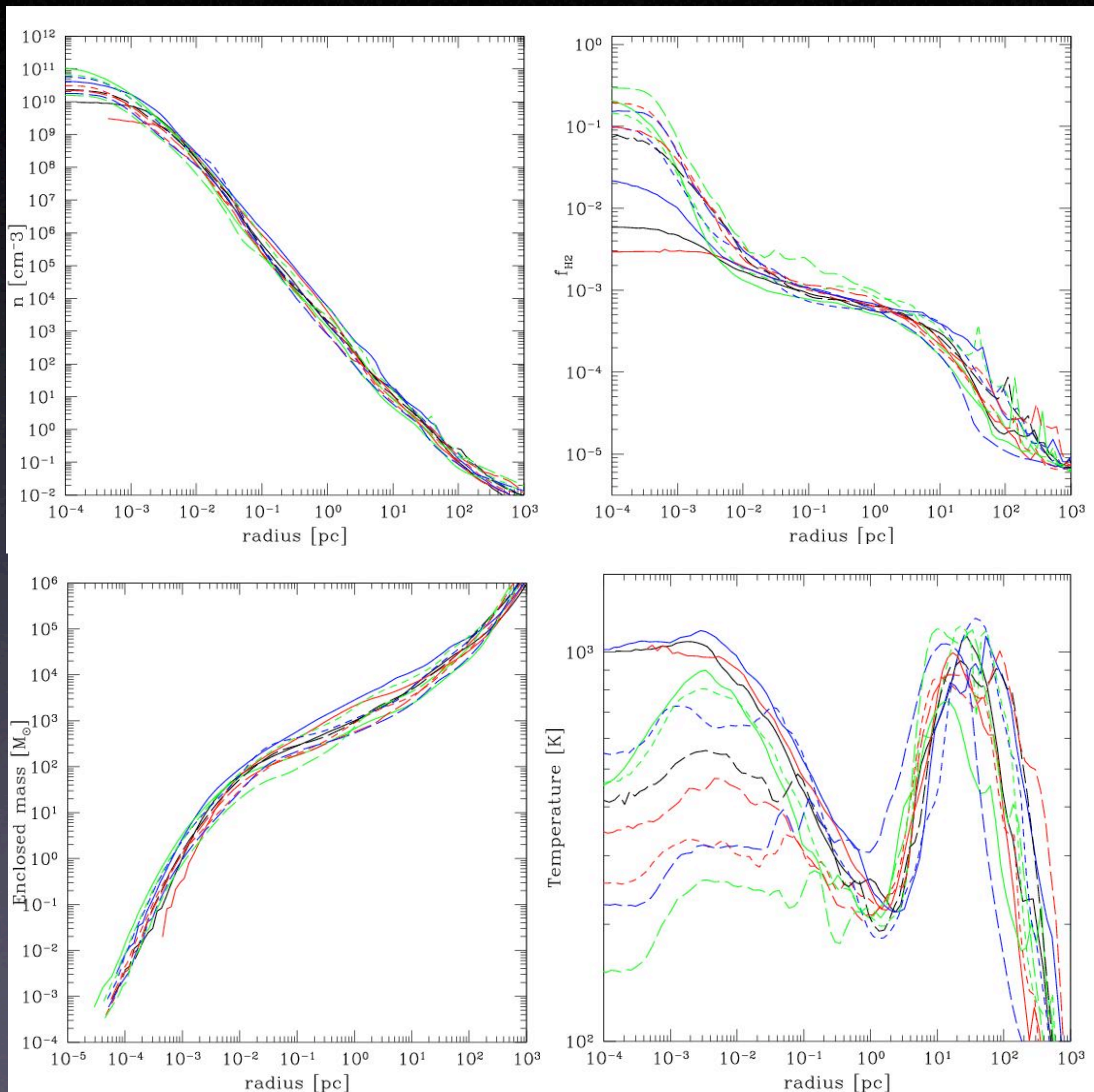
Green: est. of T_{acc}
Red: Shu model

Issue: Sims. do not include essential physics! Estimate is very crude!

This is bad! Lots of things depend on estimate of Pop III IMF!

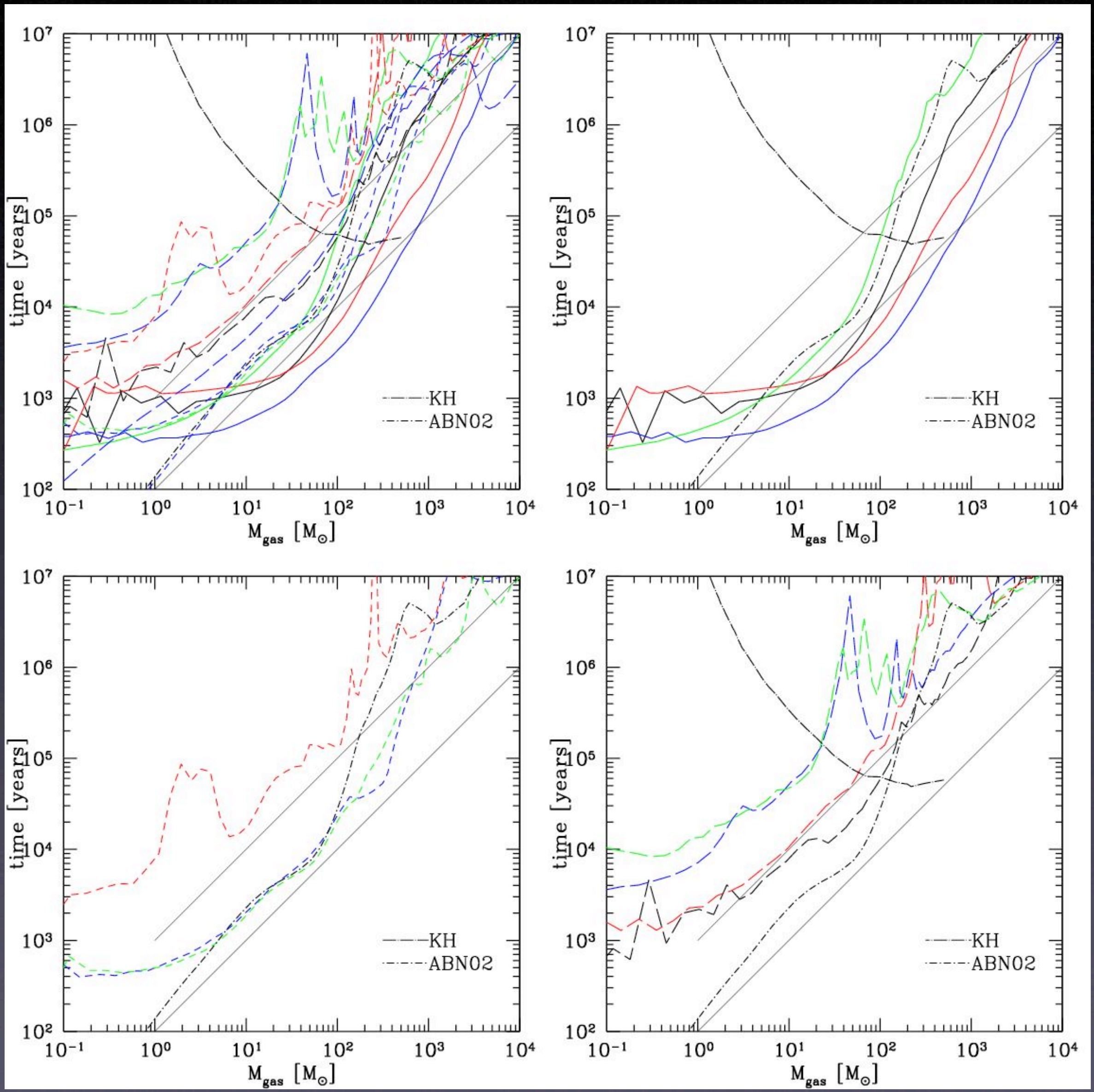
Is this result robust?

Test: many realizations, multiple box sizes.



The results generally look robust...

Closer examination of accretion rates shows systematic differences!



Increased box size - lower accretion rate!

Previous results overestimate Pop III masses!

The varied fates of Population III Stars

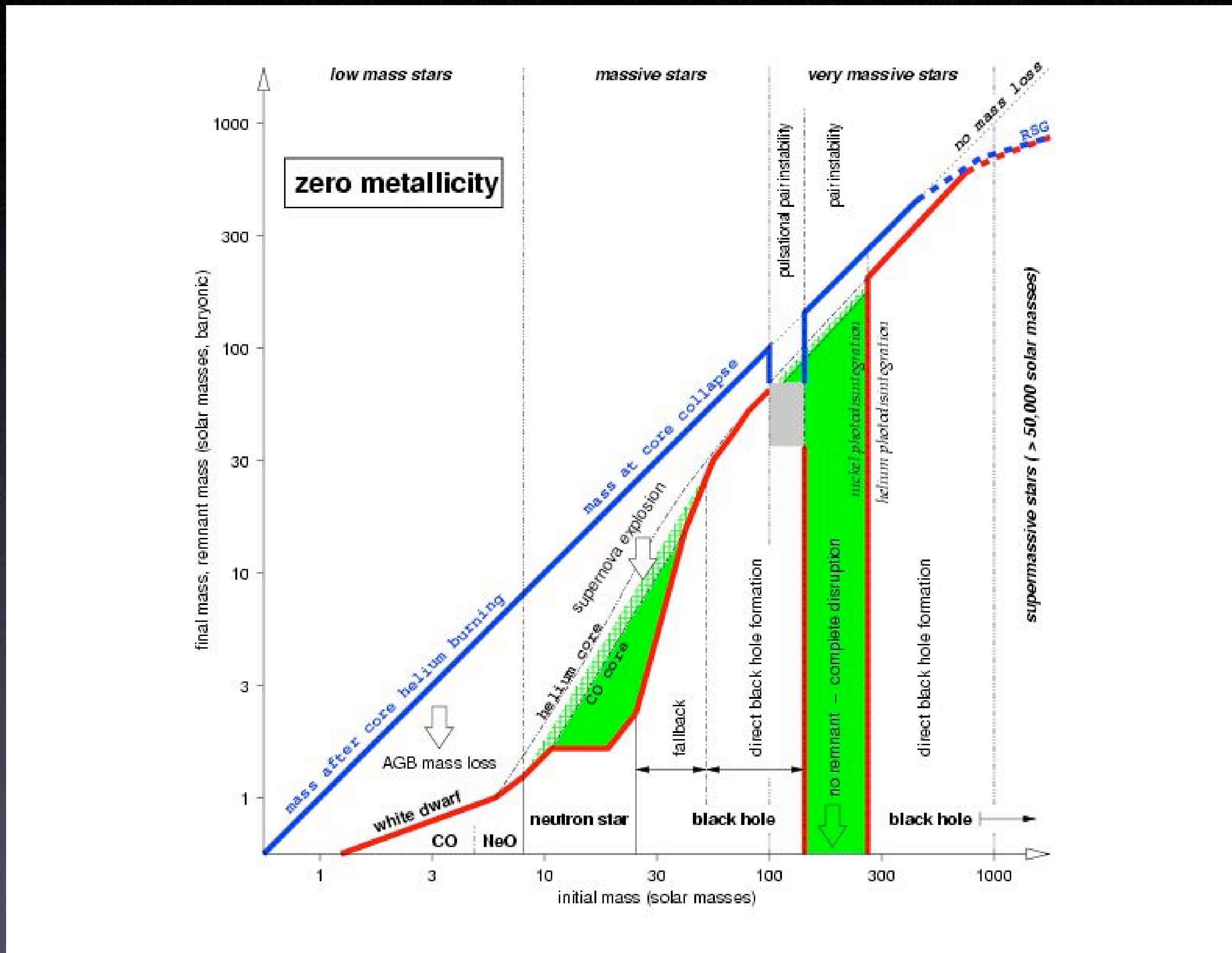
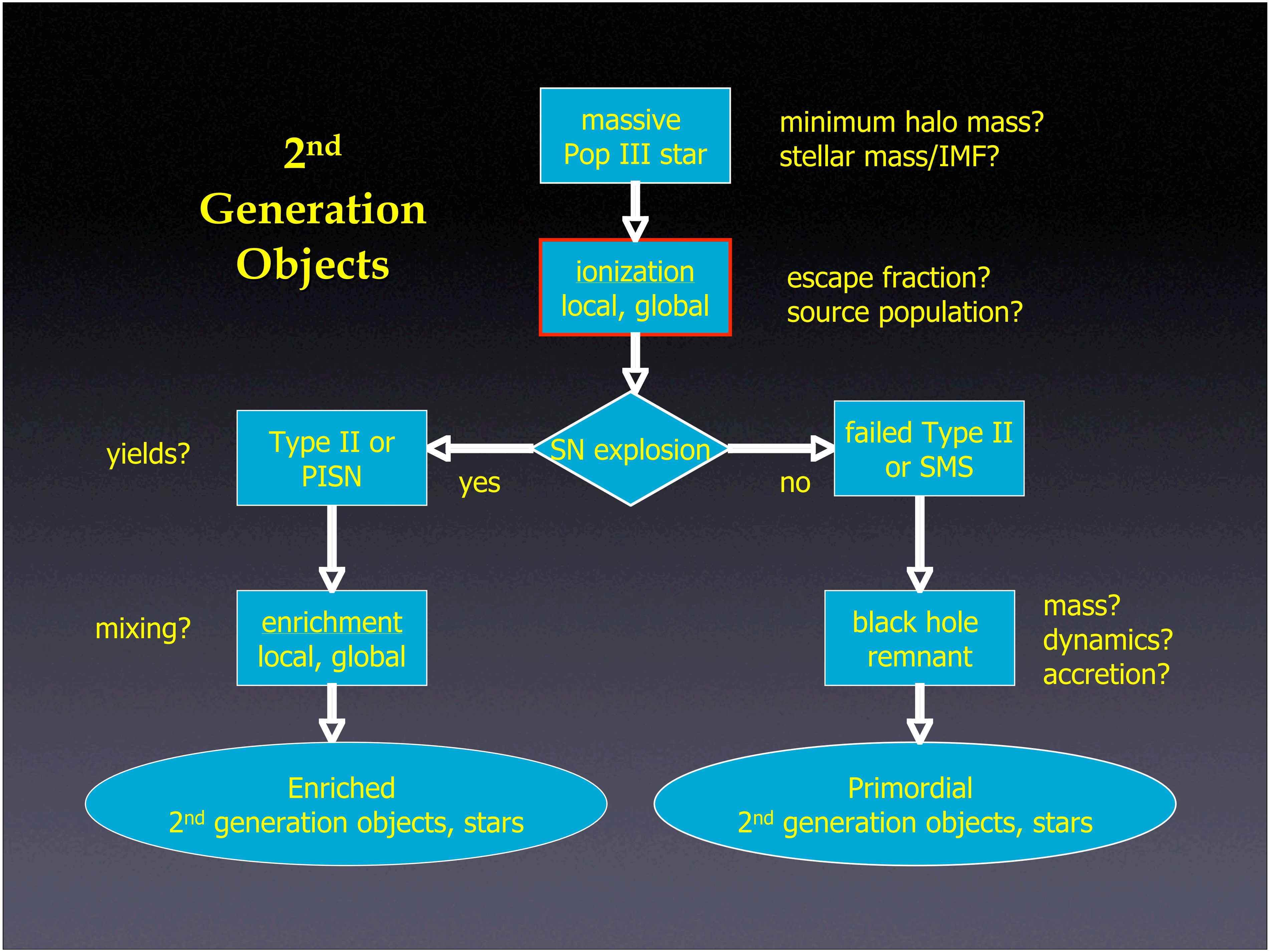
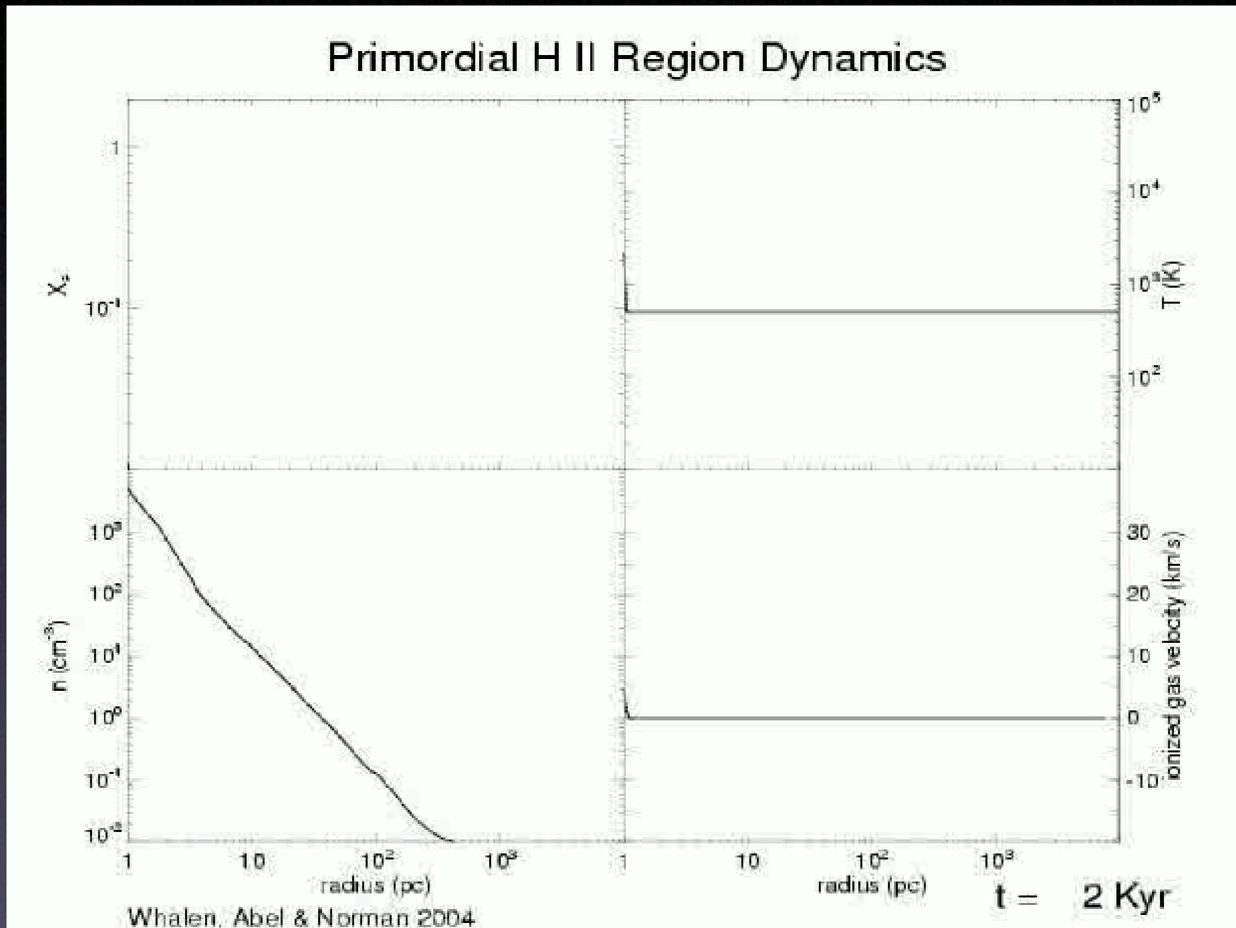


Image courtesy Alex Heger (T-6, LANL)


2nd Generation Objects
massive Pop III star
minimum halo mass?
stellar mass/IMF?
ionization local, global
escape fraction?
source population?
SN explosion
yes
no
yields?
Type II or PISN
failed Type II or SMS
mixing?
enrichment local, global
black hole remnant
mass?
dynamics?
accretion?
Enriched 2nd generation objects, stars
Primordial 2nd generation objects, stars

Feedback: HII regions from Population III stars



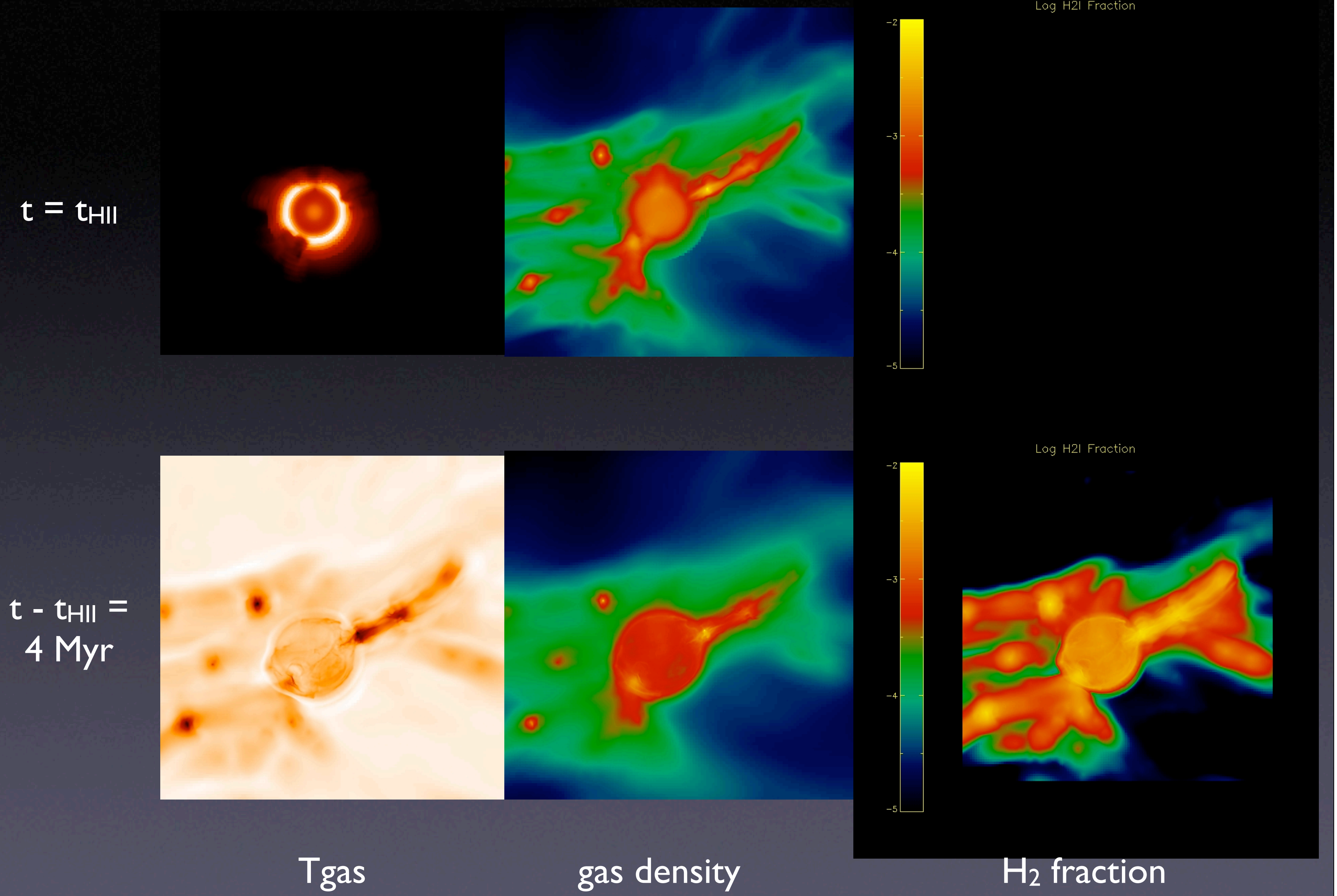
120 $M_\odot$ star, t_{star} ~ 2.5 Myr

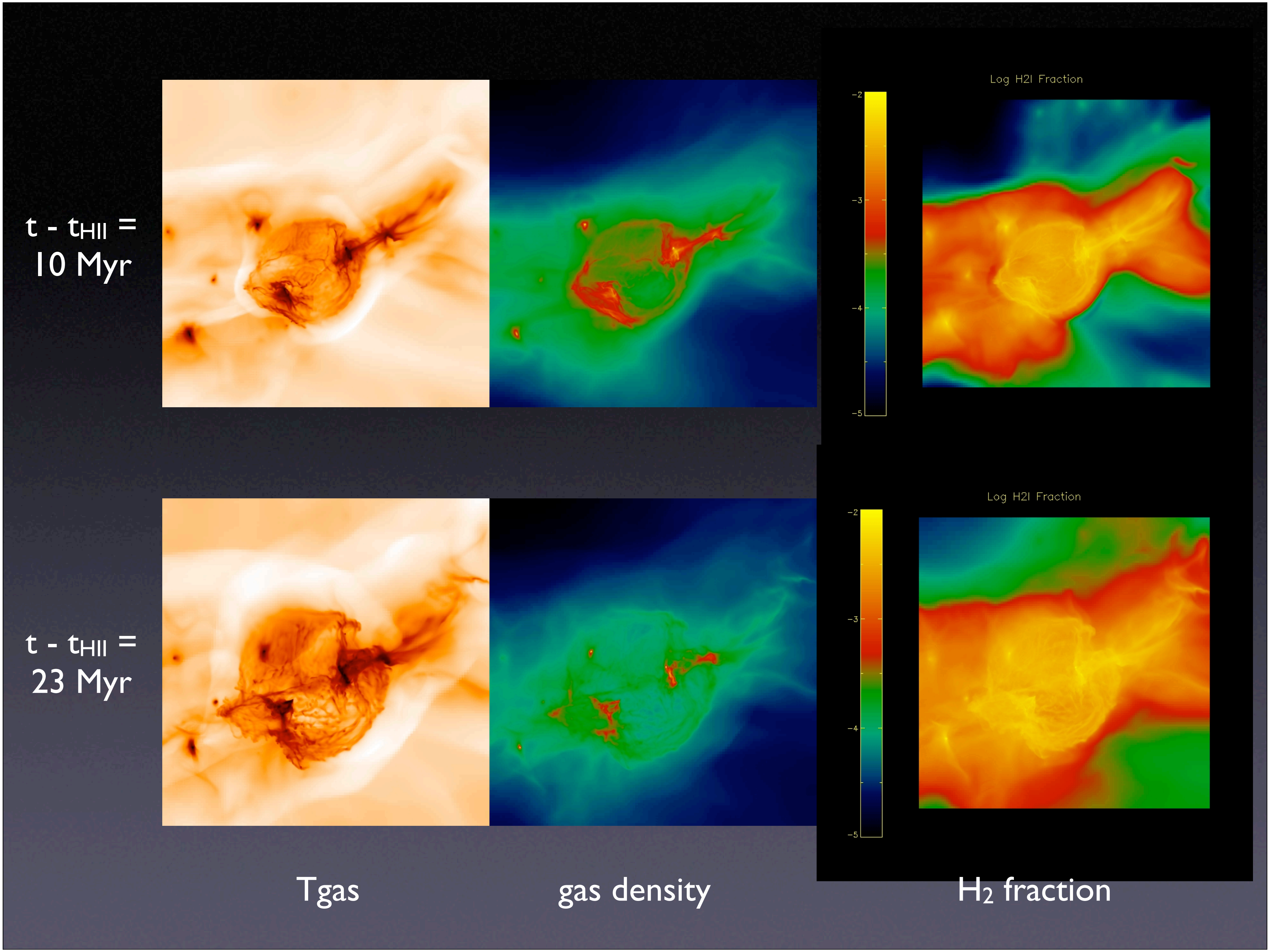
Movie c/o Dan Whalen (Whalen et al. 2004, ApJ, 610, 14-22)

3D simulations of HII regions from Population III stars

- Start with 3D AMR cosmology calculation at $t = t_{star}$
- Combine 1D and 3D results:
  - Whalen et al. results within FS halo
  - 3D ray-tracing outside of halo to determine full extent of cosmological HII region
- Turn AMR simulation back on with full nonequilibrium chemistry and follow evolution until collapse of next object!
- We observe a second primordial star forming 23 Myr later, in a halo that would not otherwise form a star for more than 75 Myr

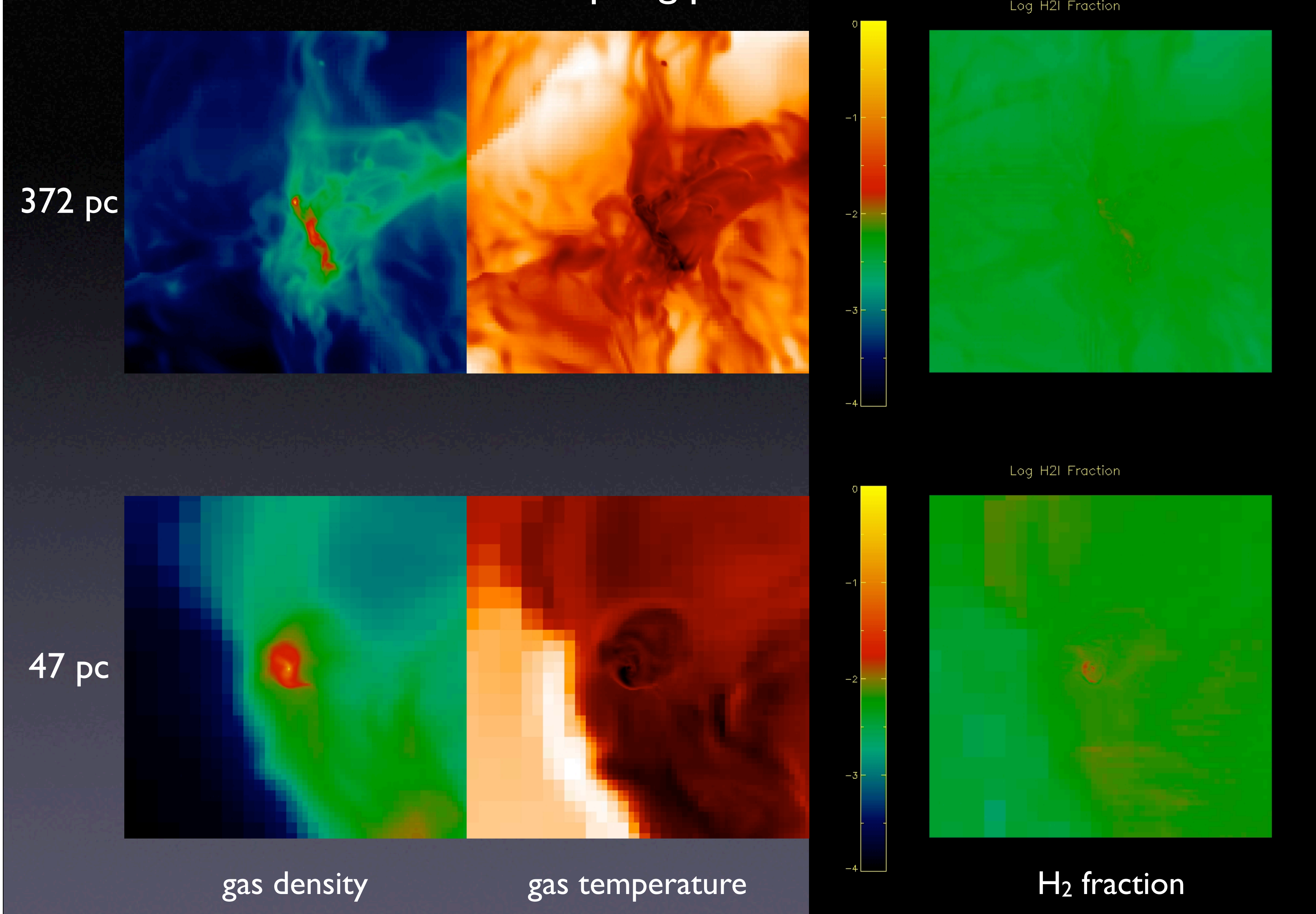
FOV = 1.5 kpc (proper)





t - tHII =
10 Myr
t - tHII =
23 Myr
Log H2I Fraction
-2
-3
-4
-5
Log H2I Fraction
-2
-3
-4
-5
Tgas
gas density
H2 fraction

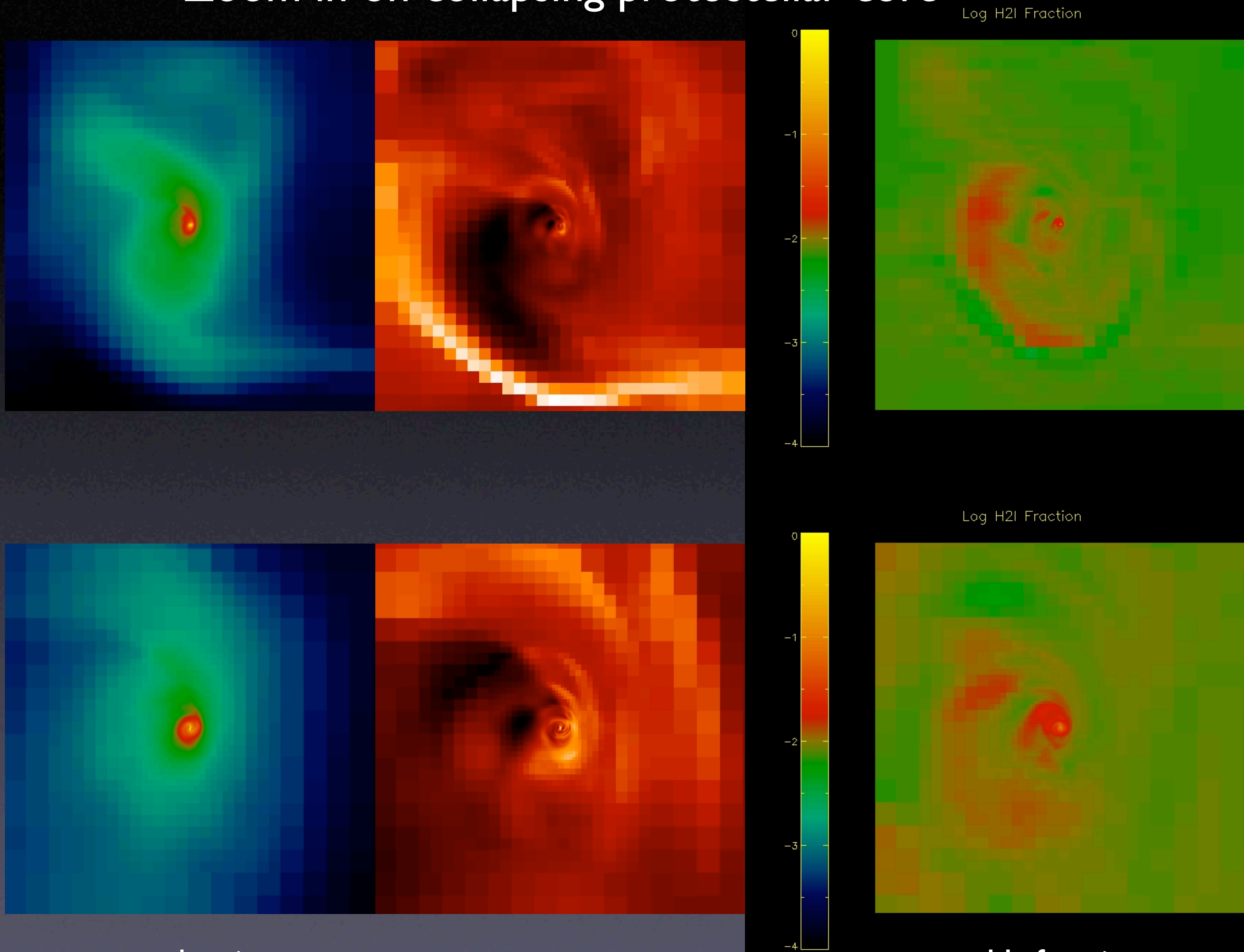
Zoom in on collapsing protostellar core



Zoom in on collapsing protostellar core

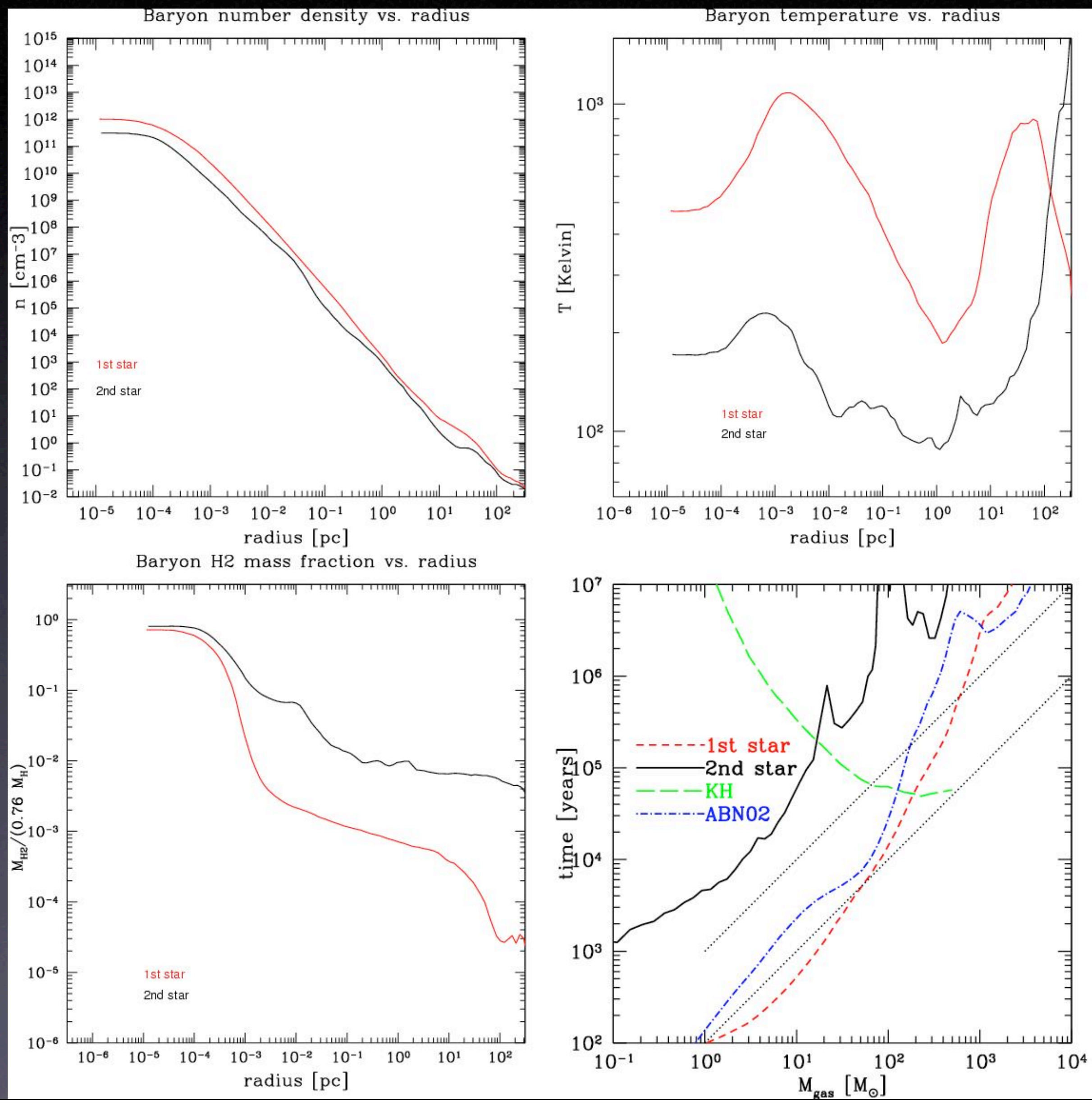
6 pc

1.5 pc



gas density | gas temperature | H_2 fraction

Comparison of "1st star" and "2nd star" in same box



Feedback: Population III Supernovae

- A crude estimate of relative energies:

  $E_{bind}(M_{halo} \sim 5 \times 10^5\ M_\odot) \sim 10^{51}$ ergs

  $E_{SN}\ (M_{PopIII} \sim 30\ M_\odot) \sim 10^{51}$ ergs

  $E_{SN}\ (M_{PopIII} \sim 250\ M_\odot) \sim$ PISN: 10^{53} ergs $\gg E_{bind}$!

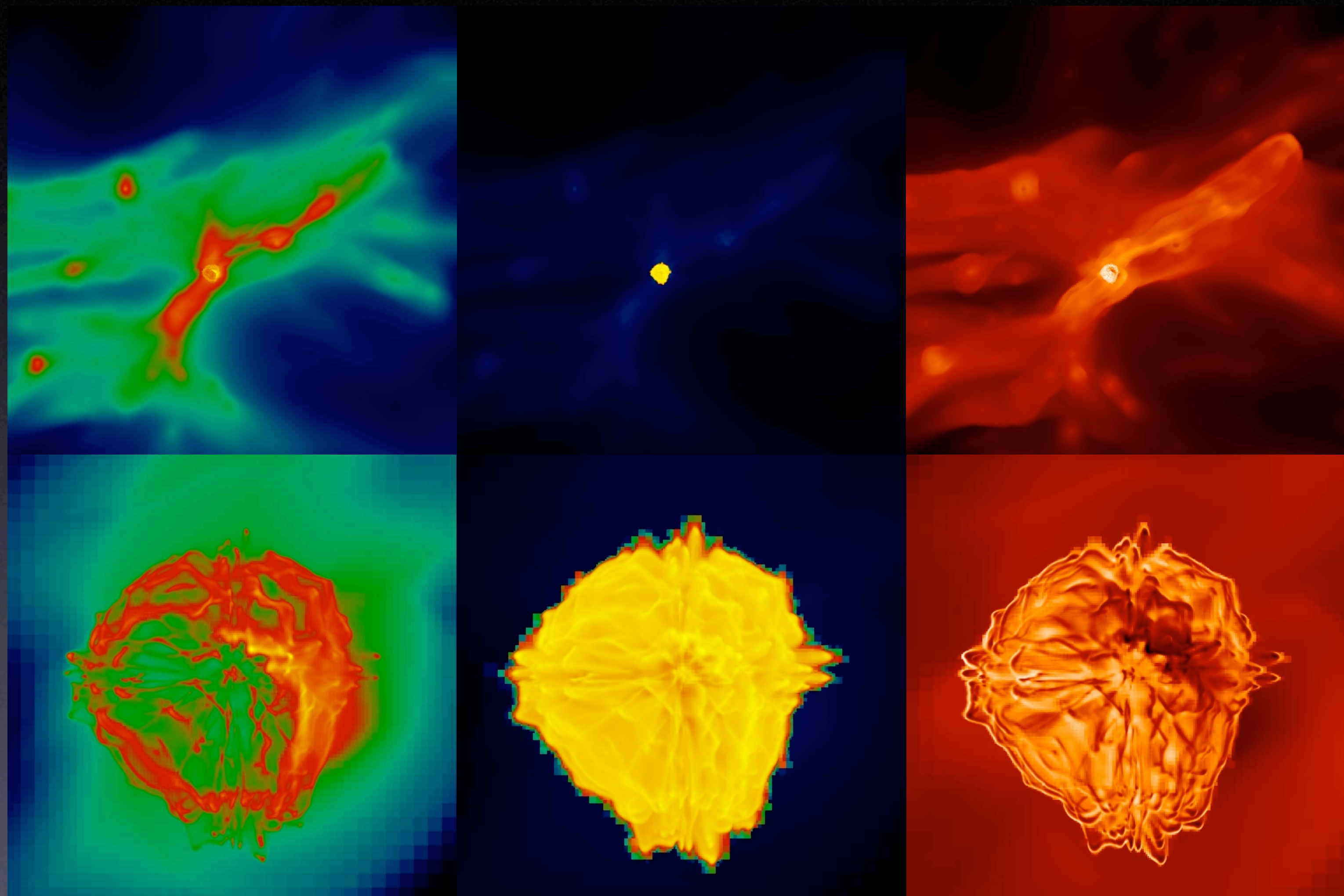
- Population III supernovae may completely disrupt their parent halos! (metal propelled to large distances)

- Population III stars: nucleosynthetic signatures?

Obligatory pretty SN pictures (right off the supercomputer)

1.5 kpc
(proper)

94 pc



gas density

metal density

gas temperature

30 $M_{\odot}$ star,
$E_{SN} = 10^{51}$ ergs
$t\text{-}t_{SN} = 6 \times 10^5$ yrs

Conclusions

- Population III stars set the stage for later epochs of star formation through radiative, chemical, mechanical feedback (maybe also seeds of SMBHs?)

- Previous simulations appear to have overestimated the IMF of Population III stars by approximately an order of magnitude

- HII regions from extremely massive Population III stars may have a positive feedback effect on later generations of (primordial) star formation

- Pop III supernovae, particularly if very massive, have the potential to enrich large volumes of the universe with metals at high redshift

Potentially useful recent review articles

"The Formation of Primordial Luminous Objects" E. Ripamonti & T. Abel, 2005, astro-ph/0507130

"The First Cosmic Structures and Their Effects," B. Ciardi & A. Ferrara, 2005, Space Science Reviews, 116, 625-705 (astro-ph/0409018)

"The Formation of the First Stars in the Universe," S. Glover, 2005, Space Science Reviews in press (astro-ph/0409737)

"The First Stars," V. Bromm & R. Larson, 2004, ARAA, 42, 42-79 (astro-ph/0311019)

"In the Beginning: The First Sources of Light and the Reionization of the Universe," R. Barkana & A. Loeb, 2001, Physics Reports, 349, 125-238 (astro-ph/0010468)